Batching Effects on Properties of Recycled Concrete Aggregates for Airfield Rigid Pavements

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Abstract

The use of recycled concrete aggregates (RCA) as a substitute for natural aggregates in new concrete produces both economic and environmental advantages. The majority of recycled concrete aggregate applications for pavements have been primarily applied to support layers for roads and airfields. This paper summarizes initial work completed in partnership with the O'Hare Modernization Program to examine the effect of recycled concrete aggregates (RCA) on the concrete's fresh and strength properties for airfield rigid pavement applications. A recent method proposed for batching and mixing recycled concrete aggregate called the two-stage mixing approach (TSMA) was evaluated in order determine its effect on the concrete's fresh and strength properties relative to virgin aggregate concrete (VAC). The principle process for the TSMA is initially coating the recycled aggregates with cementitious paste to improve the uniformity and strength of the interfacial transition zone. This paper reports the results of an experimental program in which different percentages of recycled coarse aggregates were substituted for virgin coarse aggregates. After employing the TSMA, the workability of RCA concrete was similar to the virgin aggregate concrete. Based on the compressive and the splitting tensile strength results, the RCA should meet current strength requirements for construction of airfield concrete pavements.

1.1 Introduction

Recycling operations can conserve natural aggregate sources while reducing construction costs due to lower aggregate material and transportation costs. In recent years, recycling of concrete materials into recycled aggregate has been proven to be commercially viable and technically sound for non-structural applications (1). At the present time, utilization of recycled concrete aggregate (RCA) in pavements is primarily applied to support layers for roads and airfields (2, 3). It is anticipated that there will be a continued supply of concrete waste materials, depletion in readily available natural aggregate sources, increased pressure to recycle, and in certain countries a shortage of disposal sites. Research on recycled aggregate concrete will continue to determine the feasibility of its use, potential new applications, and its impact on durability of the intended structures.

Overall, literature reports that recycled aggregates typically are of lesser quality compared with virgin aggregates. These technical problems includes potentially weaker interfacial transition zones, pores and cracks in the crushed concrete, potentially high levels of sulfates and chlorides, other impurities, unhydrated cement, poor particle size grading, and higher variation in quality (4,5). There have been an increasing number of studies on the influence of RCA as partial or total replacement of virgin aggregates and its effect on the mechanical properties and durability of RCA concrete (6). Very few studies have focused on RCA for airfield rigid pavement surface (7,22). The RCA concrete density, compressive strength, modulus of elasticity, flexural strength, tensile strength, splitting tensile strength, bonding strength can be reduced to a varying degree as well as an increase in shrinkage (4) compared to virgin aggregate concrete. The pre-requisite of applying RCA to higher performance concrete applications is to minimize these weaknesses.

RCA differ from virgin aggregates in that they are composed of natural aggregate and residual mortar. The old mortar attached to the natural aggregate is the origin of many of the RCA concrete weaknesses. Several techniques have been developed to remove as much as the adhered mortar from the RCA including chemical treatments. These methods helped to produce RCA with better quality but also generated new problems such acidic solvents leading to new pollutants and some chemicals increase the risk of alkali-aggregate reaction. The main factors influencing the old mortar content, besides the type of coarse aggregate, is the crushing operation (8). The type of crusher (e.g., jaw or impact) and the sequence of multiple crushers can minimize the amount of attached mortar and therefore, recycled concrete aggregate quality can be improved (4).

The presence of old mortar attached to the RCA surface produces two main problems: an increase in the absorption capacity of the aggregate and a weakness in the adherence between RCA and the new cement mortar. According to Etxeberria et al. (5), absorption capacity is the main factor that causes the variation of the microstructure of concrete produced using recycled aggregates with respect to conventional concrete. High RCA absorption indicates high level of mortar attachment, which leads to difficulties in controlling the properties of fresh concrete and consequently influences the strength and durability of hardened concrete. In order to reduce the influence of the higher absorption capacity RCA, researchers, such as Hansen (9) and Sagoe et al. (10), have suggested that RCA should be pre-wetted or saturated with water. Poon et al. (12) also demonstrated that the initial slump and slump loss of a RAC mixture depended on the initial moisture state of the RCA.

Besides its high absorption capacity, the old mortar adhering to the recycled aggregate can be a weak link between the RCA and new concrete matrix (13). Tam et al. (14) have proposed the Two-Stage Mixing Approach (TSMA) to strength this weakened interface zone. The principle of the TSMA is to coat the more porous, old mortar of the RCA with a cement slurry which should provide a stronger ITZ by filling in cracks and pores within the RCA. Tam et al. (13) have reported improvements in recycled concrete strength after adopting the TSMA. One potential issue with the proposed TSMA is that if the weakest zone is between the old mortar and virgin aggregate than the TSMA will likely not prove worthwhile.

Mineral admixture addition have been shown to improve the ITZ for RCA concrete (15, 16). Tam et al (14) and Kong et al. (15) suggested that the use of certain amounts of pozzolanic materials (silica fume, slag, or fly ash) into the concrete mixture combined with a multi-stage mixing process enhanced the properties of RCA concrete. According to Katz (17) and Hansen (18), if the original concrete had a higher cement content then after crushing it should retain additional binding abilities (unhydrated cement grains). The unhydrated cement eventually reacts to form new hydration products and specifically the calcium hydroxide can react with any pozzolanic admixtures to further improve the hardened properties of concrete containing RCA.

1.2 Research Objective

The purpose of this research was to evaluate recycled aggregate concrete mixtures suitable for concrete pavement construction using the Two-Stage Mixing Approach (1) and subsequently determine the effects of RCA on the concrete's fresh and strength properties compared to the results using virgin aggregates. Various concrete mixtures with different percentages of RCA and mineral admixtures as partial replacement of Portland cement were prepared.

2.0 Experimental Program

The experimental work for this research included obtaining crushed concrete from old concrete pavements at the Chicago O'Hare International Airport and characterization of the RCA physical properties (specific gravity, bulk density, moisture content, and absorption capacity). Five different concrete mixtures using virgin, blended, or 100% recycled coarse aggregates were designed and batched. Specimens were prepared for testing at various ages using a standard curing condition. The laboratory tests included fresh properties of each concrete mixture (air content, unit weight, and workability) and age dependent strength properties (compressive and splitting tensile strength).

2.1 Two-Stage Mixing Approach (TSMA)

The objective of the TSMA proposed by Tam et al. (1) was to strengthen the ITZ between the RCA and the new cement paste, which has been reported as the weakest zone in RCA (5). The concrete mixing procedure is divided into multiple stages in order to generate a thin layer of cement slurry on the surface of the RCA, which will permeate into the pores, voids, and cracks in the residual mortar and virgin aggregate. All RCA mixtures were batched with the TSMA while the virgin aggregate concrete was mixed with the standard laboratory mixing procedure.

Figure 1 shows a pictorial view of the TSMA utilized in this research for batching and mixing RCA concrete. During the first stage, RCA and cementing material are mixed for one minute followed by the addition of half of the required water and subsequent mixing for an additional minute. In the second stage, the fine aggregate, any virgin coarse aggregates, and the remaining mix water are added and mixed for a final two minutes. The TSMA was compared with the conventional laboratory mixing procedure in which the mixing pan is charged with the fine and coarse aggregates and 50% of the water and mixed for one minute. The cement is then added and mixed two more minutes. Finally the remaining 50% of mix water is incorporated and mixed three more minutes.

FIGURE 1 Two-Stage Mixing Approach for Recycled Concrete Aggregates.

2.2 Materials

The cementious materials utilized in this research included Type I Portland cement (PC), Class C Fly Ash (FA), and Silica Fume (SF). The physical characteristics of the cementitious materials are given in Table 1 (19).

TABLE 1 Physical Properties of Cementitious Materials

Material	PC	FA	SF
Density (g/cm^3)	3.15	2.5	2.2
Specific surface (m^2/kg)	272	410	20,000
Average grain diameter (μm)	7.6	5.0	0.1

Three separate aggregates sizes were blended in order to produce a well-graded aggregate to minimize the water demand, provide and maintain adequate workability, improve consolidation, and minimize finishing effort. The individual gradations of the virgin aggregate (crushed limestone) and RCA (CA-7 and CA-16) and virgin fine aggregate (FA-02) were chosen to follow the requirements of the Illinois Department of Transportation, Standard Specification for Road and Bridge Construction (20). Initially, the RCA was separated into individual sizes through sieving of the crushed concrete material and then re-blended in order to fit a desired combined grading.

Figure 2 and Table 2 shows the grading of the coarse and fine aggregates. Table 3 shows the physical properties of the virgin and recycled aggregates. The RCA were kept in a moisture condition of approximately 80 percent of its absorption capacity in order to reduce the loss of mixing water into the aggregate pores during batching. The mix water was adjusted to account for the expected absorption of the RCA. The virgin coarse aggregates were batched in the oven dry condition and the target water content adjusted for the aggregate absorption.

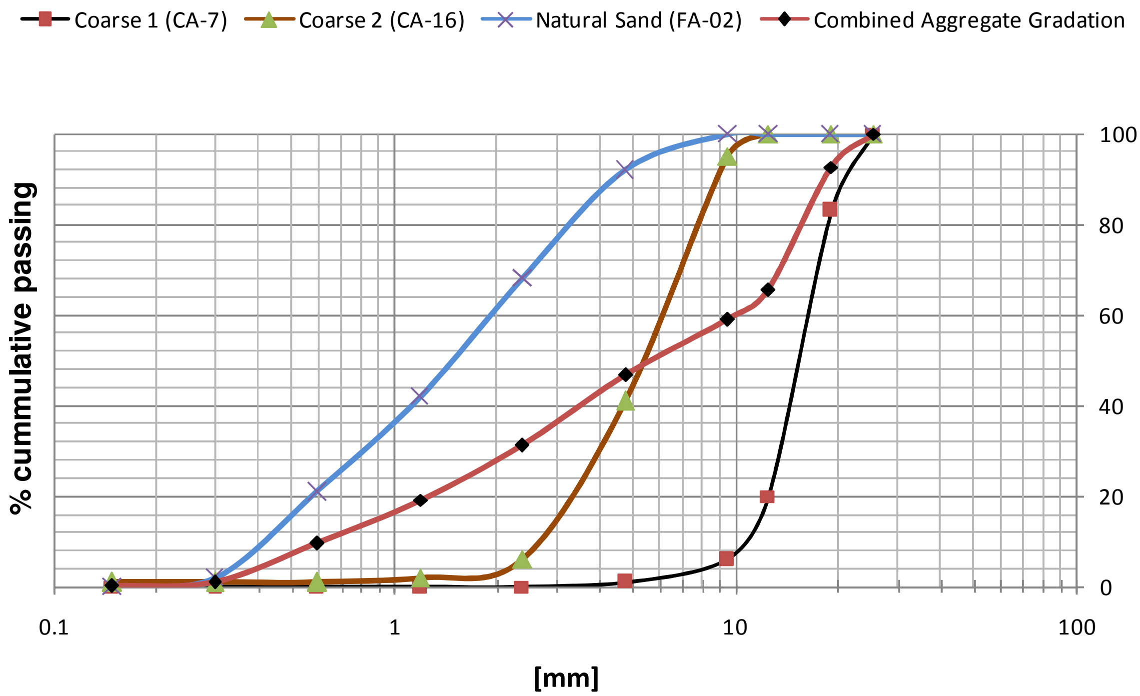

FIGURE 2 Individual fine and coarse aggregate gradations and combined target grading for the concrete mixtures.

TABLE 2 Sieve Analysis of Fine, Coarse, and Target Aggregate Grading.

Sieve		% Cumulative passing			
		Sand	Coarse 1	Coarse 2	Combined Target Grading
U.S.	mm	FA-02	CA-16	CA-7	
¾ in	19	100%	100%	83%	93
½ in	12.5	100%	100%	20%	66
3/8 in	9.5	100%	95%	6%	59
#4	4.75	92%	41%	1%	47
#8	2.36	68%	6%	0%	31
#16	1.18	42%	2%	0%	19
#30	0.6	21%	1%	0%	10
#50	0.3	2%	1%	0%	1
#100	0.15	0%	1%	0%	0

TABLE 3 Fine and Coarse Aggregates Physical Properties

	BSG	**Absorption Capacity**
Recycled Coarse Aggregate	2.41	5.51%
Virgin Coarse Aggregate (CA-7)	2.67	1.90%
Virgin Coarse Aggregate (CA-16)	2.68	2.73%
Virgin Fine Aggregate (FA-02)	2.57	2.43%

2.3 Mixture Proportions

Five mixtures were designed for application to concrete pavements to assess the fresh and strength properties of RCA concrete as a function of RCA content and mixing procedure. The mixture proportions included a total of 517 lb/yd^3 of cementitious materials, 20% of the cementitious content was Class C Fly Ash, and a water-cementitious ratio of 0.42, which were limits set forth in the concrete specifications at the O´Hare Modernization Program. Three percentages of recycled coarse aggregates were used to replace virgin coarse aggregate: 0, 50 and 100%. Table 4 shows the final proportions for the five concrete mixtures. The concrete mixtures contained no chemical admixtures for air or workability. Macro-synthetic fibers at 0.2% volume fraction were added to the 100% RAC mixture to verify its improvement on the concrete's fracture properties (21). Silica fume (SF) was used to replace 2% of the cement in one mixture to determine if the combination of mixing procedure and silica fume would significantly improve the bond strength between RCA and new paste. All mixtures in Table 4 except the virgin aggregate concrete (VAC) used the TSMA.

TABLE 4 Concrete Mixture Constituents and Proportions

Material		Content (lb/yd^3)									
		VAC		50-50 Blend		100% RCA		100% RCA+ SF		100% RCA FRC	
Water		217		217		217		217		217	
Type I Cement		414		414		414		398		414	
Class C Fly ash		103		103		103		103		103	
Silica Fume		0		0		0		16		0	
Coarse Aggregate	Virgin (CA-7)	43%	1429	21%	713	0%	0	0%	0	0%	0
	Virgin (CA-16)	12%	400	6%	202	0%	0	0%	0	0%	0
	Recycled	0	0	28%	825	55%	1649	55%	1647	55%	1649
Fine aggregate		45%	1439	45%	1439	45%	1439	45%	1437	45%	1439
Synthetic Macrofibers		0		0		0		0		3	

3. Results

The following section summarizes the testing results of the study.

3.1. Evaluation of Fresh Properties of RAC

Table 5 shows the fresh properties of the concrete mixes, which includes slump, air content, and unit weight. The slump test value for the 100% RCA concrete was higher than expected which indicates the TSMA with higher initial absorbed moisture reduces the negative workability effects associated with RCA. The addition of fibers and silica fume reduced the slump test results as expected.

TABLE 5 Fresh Properties of Virgin and Recycled Coarse Aggregate Concretes

MIX	SLUMP (in)	AIR CONTENT (%)	UNIT WEIGHT (lb/ft^3)
100% Virgin	5.0	3.2	146.4
50-50 Virgin-RCA	4.5	3.2	145.8
100% RCA	7.0	3.4	149.2
100% RCA+ SF	3.0	2.5	142.8
100% RCA + Fibers	2.2	2.5	145.0

Compressive Strength

The concrete compressive strength was estimated using 100 mm by 200 mm cylindrical specimens according to ASTM C39. The reported compressive strength value is the average of three measurements tested at the ages of 1, 7, 28 and 90 days. As seen in Table 6 and Figure 3, for all test ages, the compressive strength of the recycled aggregate concrete was similar to the virgin aggregate concrete. The compressive strength of the RCA concrete containing silica fume appeared to be higher than that of the RCA concrete and VAC especially at 28 and 90 days. An analysis of variance was done to compare compressive strength for the various percentages of recycled aggregates (0%, 50%, and 100%). As shown in Table 7 with 95% confidence, there was no statistical difference between the compressive strength of the samples at the various percentages of recycled aggregates (p-value > 0.05). This means the compressive strength was not affected by the increase in the percentage of recycled aggregates which suggests the TSMA likely improved the RCA concrete strength.

TABLE 6 Mean Strength Properties of Virgin and Recycled Aggregate Concretes

Measured Properties	Concrete Mixture Design				
	VAC	50-50 Blend	100% RCA	100% RCA+ SF	100% RCA FRC
Compressive Strength (psi)					
1 day	1419	1590	1229	1614	1737
7 days	3663	3792	3813	3958	3928
28 days	4961	4994	5011	6100	5213
90 days	6309	6483	6107	6988	6466
Splitting Tensile Strength (psi)	731	624	536	604	612

Table 7 Analysis of Variance of the Compressive Strength from Concrete Cylinders

Source of variation	Sum of squares	Df	MS	F	P-value
Between groups	997043	4	249261	0.054598	0.99383
Within groups	68479725	15	4565315		
Total	69476768	19			

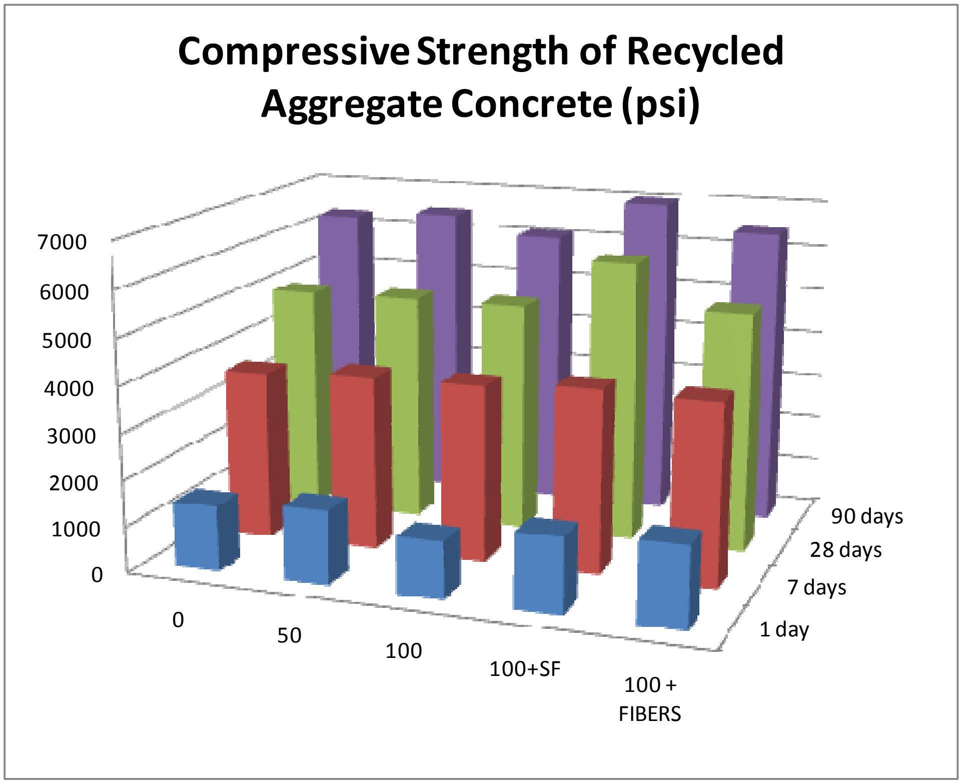

FIGURE 3 Compressive strength of virgin and recycled coarse aggregate concrete.

Splitting Tensile Strength

The concrete tensile strength was also estimated using the splitting tensile test with 100 mm by 200 mm cylindrical specimens according to ASTM C496. Figure 4 and Table 6 show the results of the tensile strength tests for the VAC and RCA concrete mixtures at 56 days only, which is an average of three specimens. Table 8 shows the results of the analysis of variance of the splitting tensile strength for the various percentages of recycled aggregates. With 95% confidence level, there was a statistical difference between the splitting tensile strength of the various RCA mixtures (p-value < 0.05) and thus percentage of recycled aggregate replacement did affect the tensile strength despite the use of the TSMA. As seen in Table 6, the mean tensile strength for the virgin coarse aggregate mixture was 25 percent greater than 100% RCA and 18% higher than 100% RCA with silica fume. The higher tensile strength of the virgin aggregate concrete is likely caused by pre-existing cracks in the recycled aggregates and residual mortar. These cracks could have been caused by the crushing process or existed in the original concrete. These cracks would not propagate very easily under compressive loading but are more able to grow when subjected to tensile stresses. Since flexural strength was not measured in this study, it is difficult to predict the trends, but its magnitude is typically 20 to 30 percent higher than split tensile strength results.

Furthermore, a recent field project at O'Hare Airport with this specific recycled concrete aggregate achieved 790 and 915 psi flexural strengths at 7 and 28 days, respectively.

Table 8 Statistical Analysis of the Splitting Tensile Strength from Concrete Cylinders by Analysis of Variance

Source of variation	Sum of squares	Df	MS	F	P-value
Between groups	58904.87452	4	14726.21	31.0980	<0.0001
Within groups	4735.413595	10	473.5413		
Total	63640.28812	14			

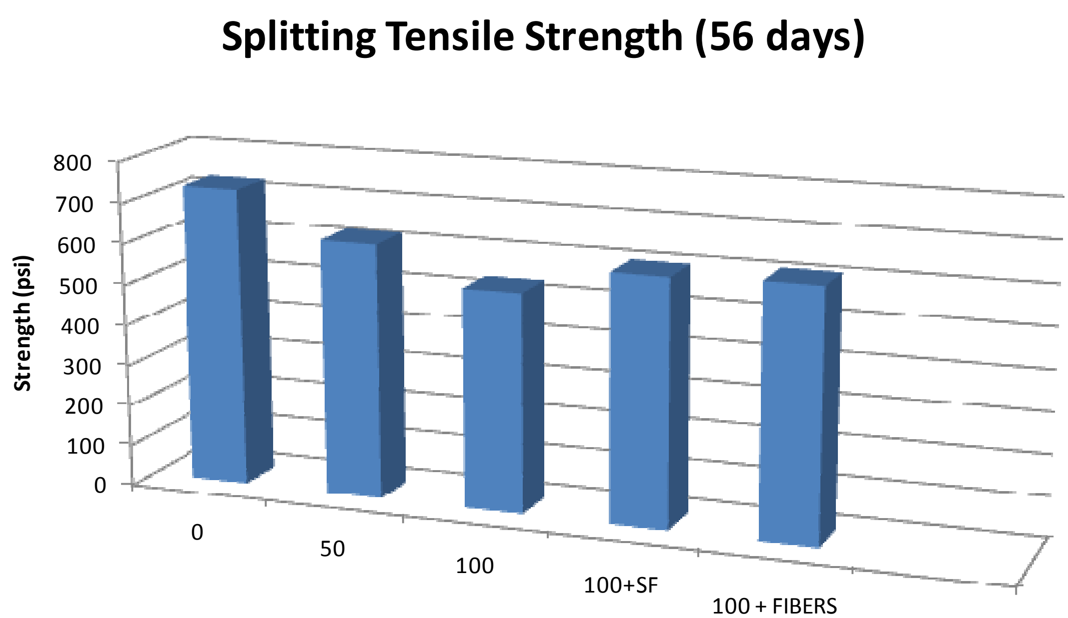

FIGURE 4 Splitting tensile strength of virgin and recycled aggregate concrete.

Conclusions

Replacement of virgin coarse aggregates with recycled concrete aggregates (RCA) typically reduces the workability and strength properties of the concrete when all other factors are held constant. A new mixing process in the literature, called the two-stage mixing approach (TSMA), has reported an improvement in RCA mixture properties without altering the mixture proportions used for virgin aggregate concrete. Four concrete batches containing varying percentages of recycled concrete aggregates were cast along with a control concrete using virgin coarse aggregates to investigate the effect of the amount of recycled aggregate, mineral admixtures, and the mixing procedure on the concrete's workability and strength properties.

The experimental results presented suggest that the TSMA can be an effective method for correcting for the expected decrease in the RCA concrete properties relative to virgin aggregate concrete given similar mixture constituents and proportions. RCA batched with moisture conditions nearing saturated surface-dried gave similar slump tests results when compared to the control mixture. The RCA mixtures with silica fume or fibers showed reduced workability as expected. According to an analysis of variance, the compressive strength of concrete using various percentages of RCA was similar to that of virgin aggregate concrete specimens. However, the splitting tensile strength of RCA was statistically different than that of the concrete mixture with virgin aggregate concrete. Since the concrete tensile strength is affected by the interface condition between the aggregate and the cement matrix, the source of reduced tensile strength could be between the virgin aggregate and original paste or the recycled aggregate and new cement paste. Despite this lower split tensile strength for RCA concrete, a recent field project at O'Hare Airport, with these RCA materials, achieved flexural strength in excess of 900 psi at 28 days. Research is currently underway to evaluate the durability aspects of RCA concrete for airfield pavements.

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References

1. Tam V., Tam C., Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach, Journal Materials Science, 42, 2007, pp. 3592–3602.
2. Saeed A., Performance Related Tests of Recycled Aggregates for Use in Unbound Pavement Layers, NCHRP Report 598, Project 4-31, National Cooperative Highway Research Program, Washington D.C, 2008.
3. Saeed A., Hammons M., Rufino D., Poole, T., Evaluation, Design, and Construction Techniques for Airfield Concrete Pavement Used as Recycled Material for Base, Final Report IPRF-01-G-002-03-5, Innovative Pavement Research Foundation, Airport Concrete Pavement Technology Program, Skokie, Illinois, 2006.
4. Tam V., Gao X., Tam C., Comparing performance of modified two-stage mixing approach for producing recycled aggregate concrete, Magazine of Concrete Research, 58, No. 7, September, 2006, pp. 477–484.

5. Etxeberria M., Vázquez E., Marí A., Microstructure analysis of hardened recycled aggregate concrete, Magazine of Concrete Research, 58, December 2006, pp. 683–690.
6. Benge J. Pena J., Ortiz I., Influence of Recycled Aggregates on Mechanical Properties of High Performance Concrete, 2008, ASEE IL/IN SECTION CONFERENCE, April 3-5, 2008, Indiana, USA.
7. Salas, A., Roesler, J., Lange, D., Properties of Recycled Aggregate Concrete, Technical Note 43 for O'Hare Modernization Program, University of Illinois, 2009.
8. Embacher E., Master of Science Thesis, Effects Of Reclaimed Mortar Content On RCA Concrete Properties, University Of Minnesota, January 2001, 147 pp.
9. Hansen T., RILEM Reported 6, Recycling of Demolished Concrete and Masonry. E&FN Spon, 1992, Bodmin, UK.
10. Sagoe C., Brown T., Taylor A., Performance of concrete made with commercially produced coarse recycled concrete aggregate, Cement and Concrete Research, 31, 2001, pp. 707–712.
11. Poon, C.S., Shui, Z.H., Lam, L., Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates, Construction and Building Materials, 18, 2004, pp. 461-468.
12. Poon C., Shui Z., Lam L., Fok H., Kou S., Influence of moisture states of natural and recycled aggregates on the properties of fresh and hardened concrete, Cement and Concrete Research 34, 1, 2004, pp. 31–36.
13. Tam V., Gao X., Tam C., Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, Cement and Concrete Research, 35, 2005, pp. 1195– 1203.
14. Tam V., Gao X., Tam C., Diversifying two-stage mixing approach (TSMA) for recycled aggregate concrete: TSMAs and TSMAsc, Construction and Building Materials, 22, 2008, pp. 2068–2077.
15. Kong D., Lei T., Zheng J., Ma C., Jiang J., Jiang J., Effect and Mechanism of Surface-Coating pozzolanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete, construction building materials, in press, 2010.
16. Etxeberria M., Vázquez E., Marí A., Barra M., Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cement and Concrete Research, 37, 2007, pp. 735–742.
17. Evangelista L., de Brito J., Mechanical behavior of concrete made with fine recycled concrete aggregates, Cement & Concrete Composites 29, 2007, pp. 397–401.
18. Hansen T., Recycled concrete aggregate and fly ash produce concrete without Portland cement, Cement and Concrete Research, Vol. 20, 1990, pp. 355-356.
19. Salas A., Delvasto S., Mejia R., Lange D., Comparison of two processes for treating rice husk ash for use in high performance concrete, article in press, Cement and Concrete Research, 2009.
20. Illinois Department of Transportation, Standard Specifications for Road and Bridge Construction, January 2007.
21. Bordelon A., Cervantes V., Roesler J., Fracture properties of concrete containing recycled concrete aggregates, article in press, Magazine of Concrete Research, 2009.

22. Hironaka,M., Cline,G., Shoemaker,N., Recycling of Portland Cement Concrete Airport Pavements - An Experimental Investigation, Naval Civil Engineering Laboratory, Port Hueneme, CA, 1987, 106 pp.